# Nanostructured Alloys as an Alternative to Copper-Beryllium

**Project Number WP-2137**
**Integran Technologies Inc.**

**ASETS Defense 2014**
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**Presented by Jonathan McCrea**

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**Standard Form 298 (Rev. 8-98)**
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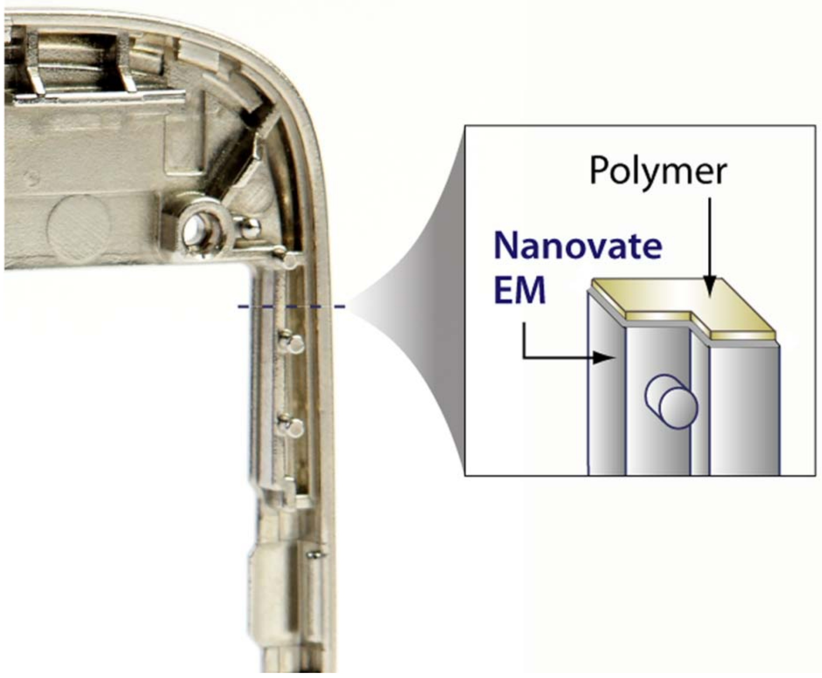
# Advanced Materials

Integran Technologies provides innovation solutions to the material selection process to improve performance and decrease weight based on our **Structural** and **Functional** Nanometal coatings and electroforms.

**Structural** – High strength / stiffness / toughening structural reinforcement of aluminum, polymers and composites or bulk electroforms.

**Functional** – High wear resistance, low friction, anti-galling, low erosion, corrosion protection, magnetic shielding, electrical conductivity.



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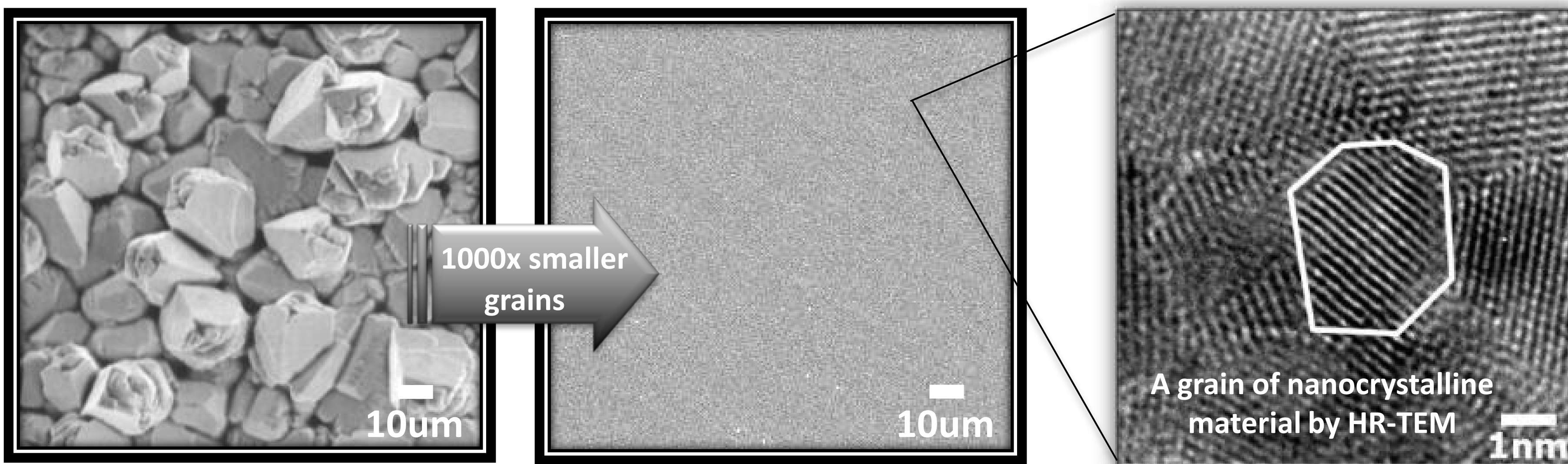
# What is a Nanostructured Metal?

**Conventional Metals** | **Nanovate™ Metals**




**Grain size = 10 – 100um** | **Grain size = ≤ 20 nm**

A Nanostructured Metal is simple a metal with an average grain size in the nanometer range (10-100nm) compared to >1μm for a conventional metal

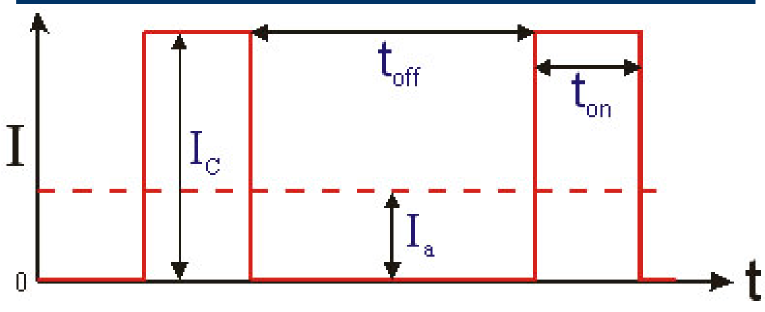
**Decreasing Grain Size Dramatically Improves Hardness and Strength**

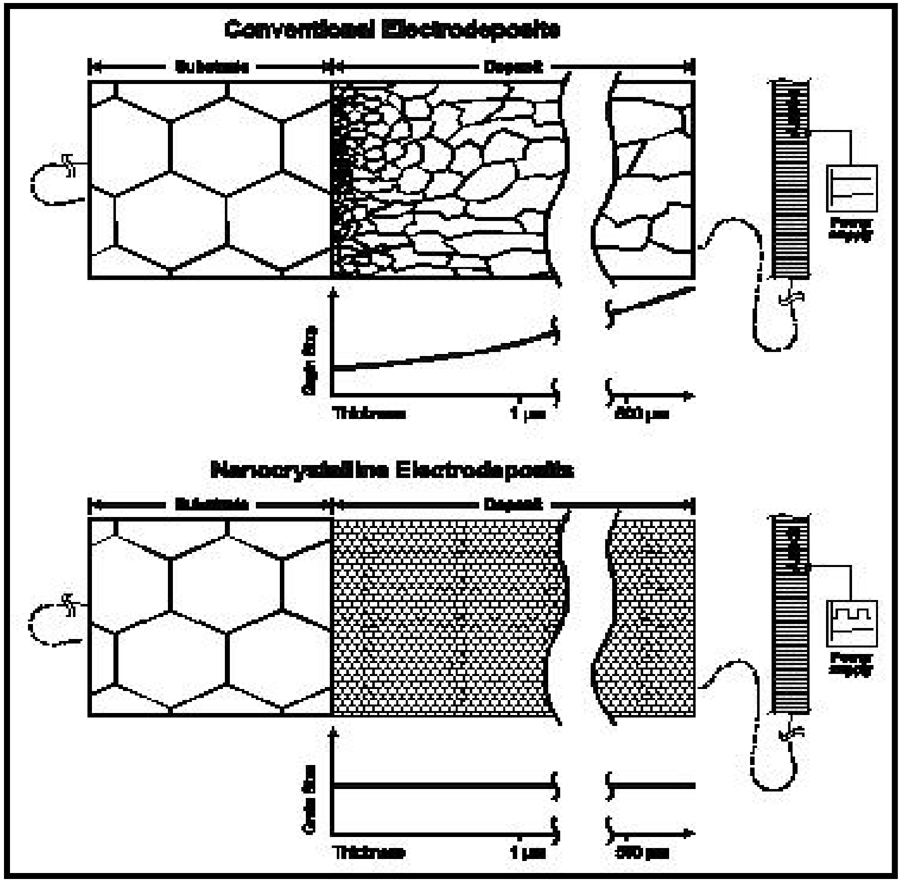
| Property | Units | Conventional Ni (20 um) | Nanovate Ni (20 nm) |
|---|---|---|---|
| Yield Strength | MPa | 100 | 900 |
| Ult.Tensile Strength | MPa | 400 | 1400 |
| Vickers Hardness | $kg/mm^2$ | 140 | 450 |

# How do we achieve unique properties?

## Microstructural Control by Pulsed Electrodeposition

Pulse Plating favors nucleation of new grains over growth of existing grains, resulting in an ultra-fine grain structure throughout the entire thickness of the coating, right from the substrate interface.




Pulsed Electrodeposition from Aqueous solutions results in the deposition of fully dense metal with a nanocrystalline grain size. At **no point** in the fabrication process are nanosized powders produced.

# Several Nanovate™ Alloys Available

## N1000 Series - *Nickel*

Good hardness, wear, and corrosion resistance as well as good strength properties. Also used for erosion protection of composites.

*Grafalloy Epic™ golf shaft - graphite/epoxy coated with Nanovate™ N1010*

## N2000 Series – *Nickel Alloy*

Higher strength than the N1000 series. Some compositions also offer magnetic shielding properties, increased resilience, or decreased CTE.

*EMI shielded cell phone casing*

*Metallix™ HEAD racquet with Nanovate™ N2015 foil*

## R3000 Series - *Cobalt*

Superior hardness, wear, and corrosion resistance; it has been validated as an environmentally friendly alternative to hard chrome. Also has excellent structural properties.

*Nanovate™ R3010 for hydraulic actuators*

## C4000 Series – *Copper*

Strong and hard, fine grained Cu being developed for electronics, high strength wires, anti-microbial and defense applications.

*Nanovate™ C4010 shape charge liner*

# Problem Statement

## The Benefits of Copper Beryllium

- Cu-Be is the **hardest** and **strongest** of any copper alloy.
- The high yield **strength** and high **stiffness** make it an ideal material for components under repeated stress and strain (spring wire, load cells, bushings, etc).
- Other advantageous properties include: good conductivity, low friction, non-galling, non-sparking, nonmagnetic, good high temperature and corrosion resistance.

## The Drawbacks of  Beryllium Copper

- Exposure to Be results in a range of diseases including lung cancer and Chronic Beryllium Disease (CBD).
- DoD employees are exposed to Be dust and fumes as a result of the wearing of Be-containing alloys during operation and during machining and other fabrication operations
- An **environmentally benign alternative** is required for worker health and safety

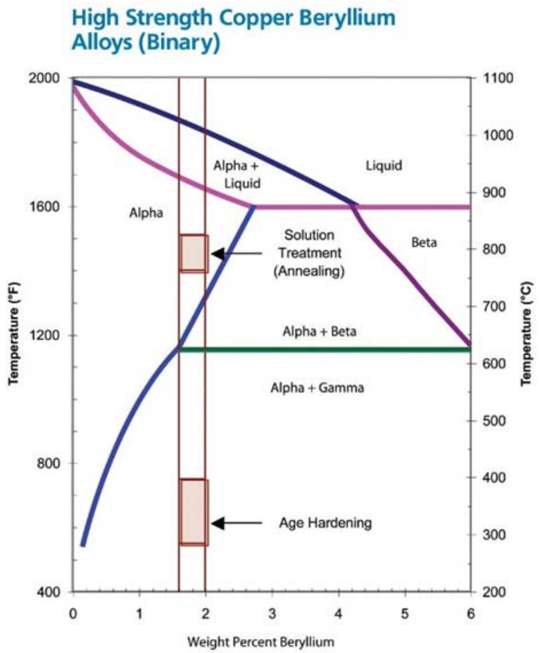
# Technical Objective of SERDP

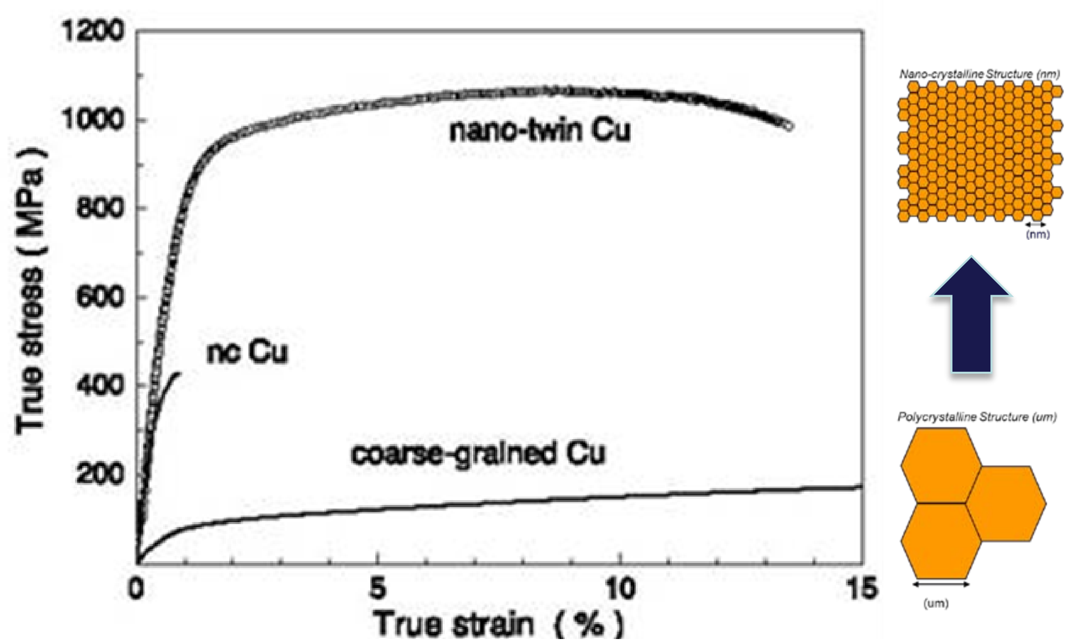
- **Develop and validate a cost-effective and robust nanocrystalline alloy electroplating/electroforming process that is capable of producing material that conforms to property requirements for current and future copper-beryllium alloy needs/ applications**

- **Demonstrate with three distinct product forms:**
  - **1) Bulk material for bushing applications;**
  - **2) Nanometal/composite for high specific strength/stiffness components; and**
  - **3) Nanometal cobalt/copper enabled conductor wire**

# Technical Approach

- **Instead of employing age hardening with beryllium bearing copper alloys (or work hardening with current CuBe alternatives), Integran will improve the properties of copper alloys through grain size reduction / refinement to the nanostructured regime**



# Technical Approach

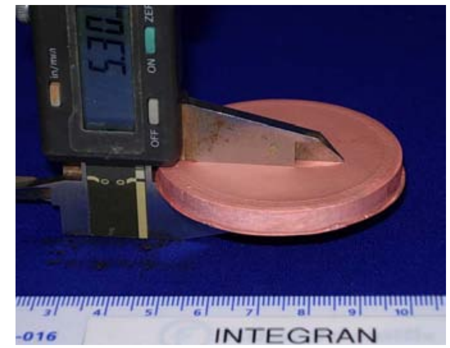
**Phase I consisted of two main activities:**

1) **Core technology development**
   - ♦ Nanostructured alloy development and fundamental material property characterization

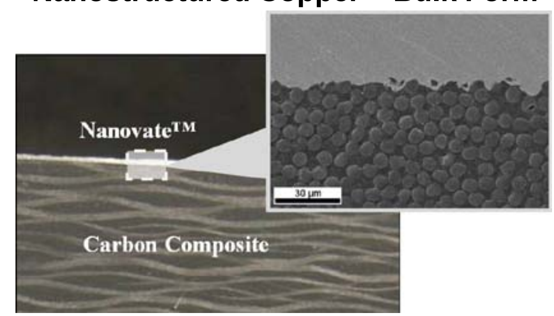
2) **Proof-of-concept demonstration** for three proposed application types
   - ♦ Bulk forms for bushings
   - ♦ Nanometal/composite hybrids for components typically formed from sheet metal
   - ♦ Nanometal hybrid wire

**Phase II consisted:**

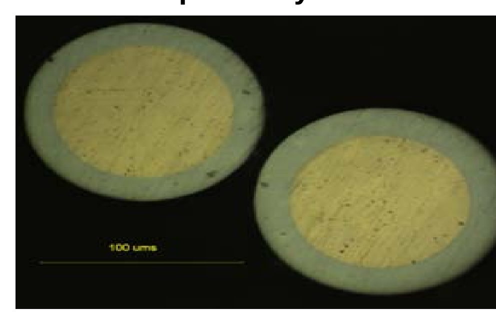
1) **Demonstration and Validation** of the three application types explored in Phase I




Nanostructured Copper – Bulk Form

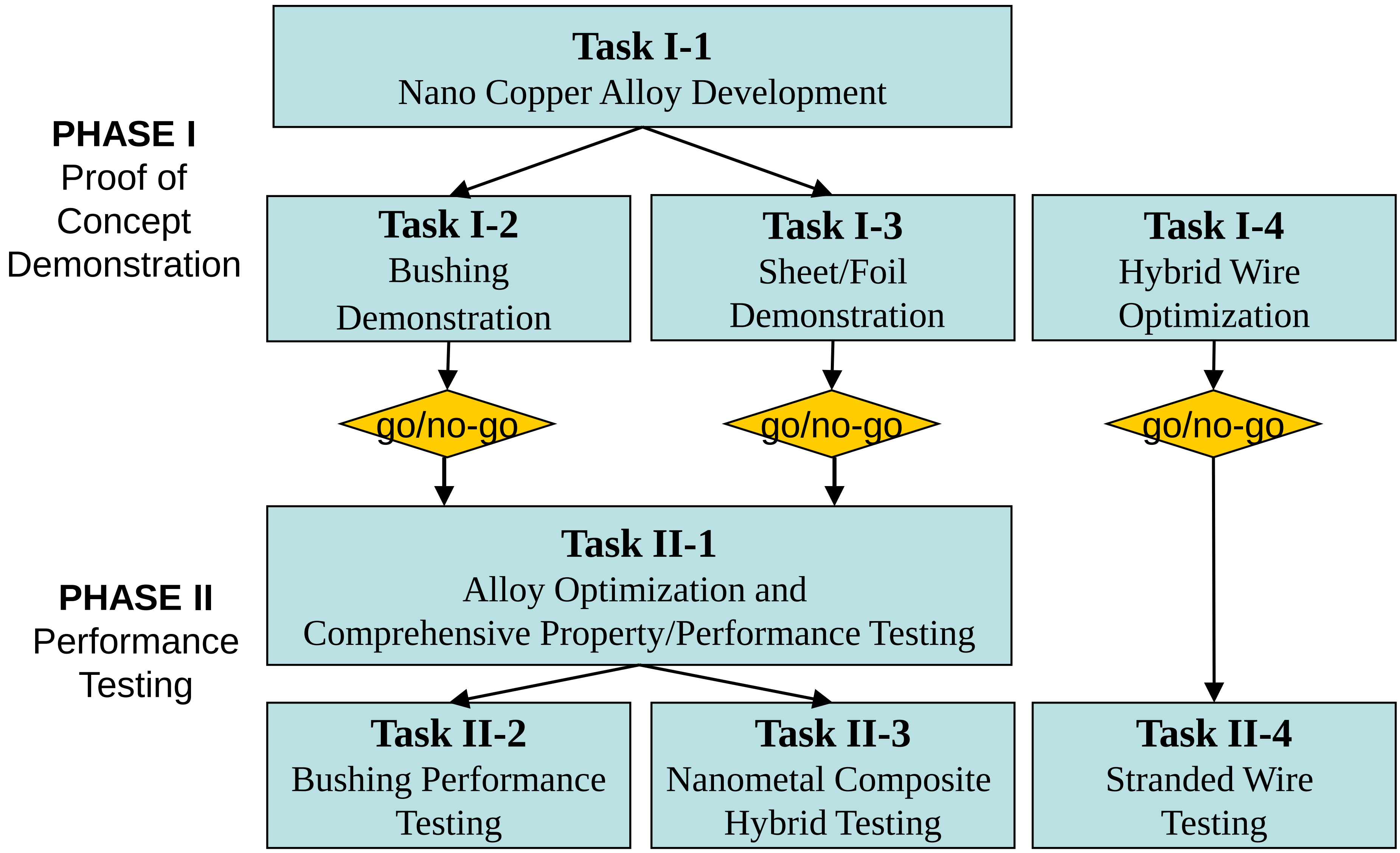



Nano/Composite Hybrid – Sheet Form



NanoConductor – Wire Form

# Technical Approach



# Summary of Phase I Alloy Development

| System | Roughness ($R_a$, µm) | Microhardness (HV) | Taber Wear (mg/1000) | Friction (vs. 440C SS) | Ductility |
|---|---|---|---|---|---|
| C17200 TF00 | -- | 393 ± 10 | 72 ± 5 | 0.8-1.0 | Low |
| nCu (Pyro) | 0.7-0.8 | 200 ± 10 | 76 ± 14 | 0.7-0.8 | Medium |
| nCu (Sulfate) | 0.8-1.0 | 200 ± 10 | N/D | 0.8-0.9 | Medium |
| nCu + TF/D | 0.5 | 223 ± 9 (low D)<br>245 ± 3 (high D) | 34 ± 7 (low D)<br>9 ± 2 (high D) | 0.3-0.4 (low D)<br>0.7-0.8 (high D) | Low |
| nCuSn | N/D | 400-500 | N/D | 0.6-0.8 | Very low |
| nCuNi | 0.5-0.6 | 350-450 | 27 ± 7 | 0.7-0.9 | Low/medium |
| nCo-alloy | 0.4-0.5 | 440-500 | 18-19 | 0.3-0.5 | Medium/high |
| nNiCo | 0.8 | 477 ± 11 | 17 ± 2 | 0.7-1.0 | Medium |
| nNiCo + GR | 2.7 | 488 ± 38 | N/D | 0.3-0.4 | Low |
| nNiCo + GR/D | 2.1 | 504 ± 13 | 3 ± 2 | 0.9-1.1 | Low |

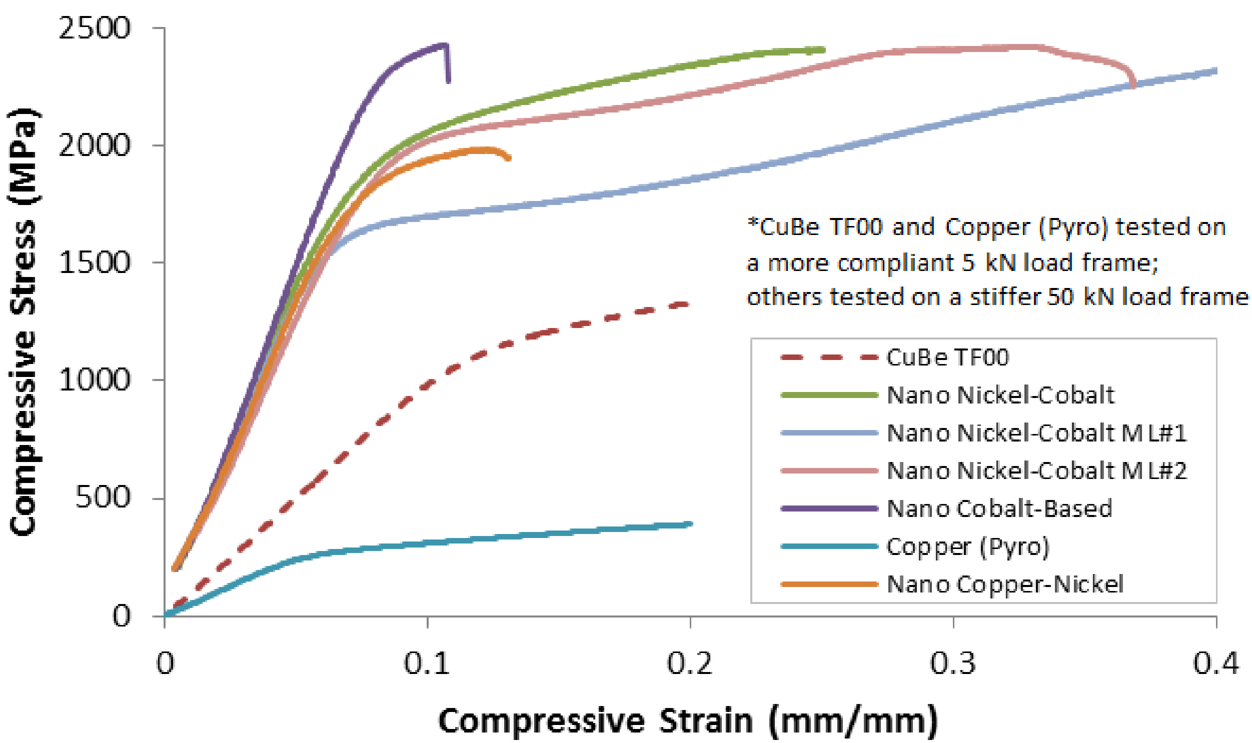
# Nanometal Bushing Performance Testing

## Background

- Cu-Be alloys still represent the best combination of strength, wear properties and cost for highly loaded bushing applications
- In Phase II, various electroformed nano alloys (Co, NiCo, CuNi and nCu) were tested and evaluated as an alternative to Cu-Be
- Performance testing included:
  - Tensile and compressive strength
  - Coefficient of friction against various ‘pin” materials
  - Galling resistance
  - High-load subscale bushing test

# Mechanical Strength in Compression

- **Uniaxial Compression Testing (ASTM E9)**

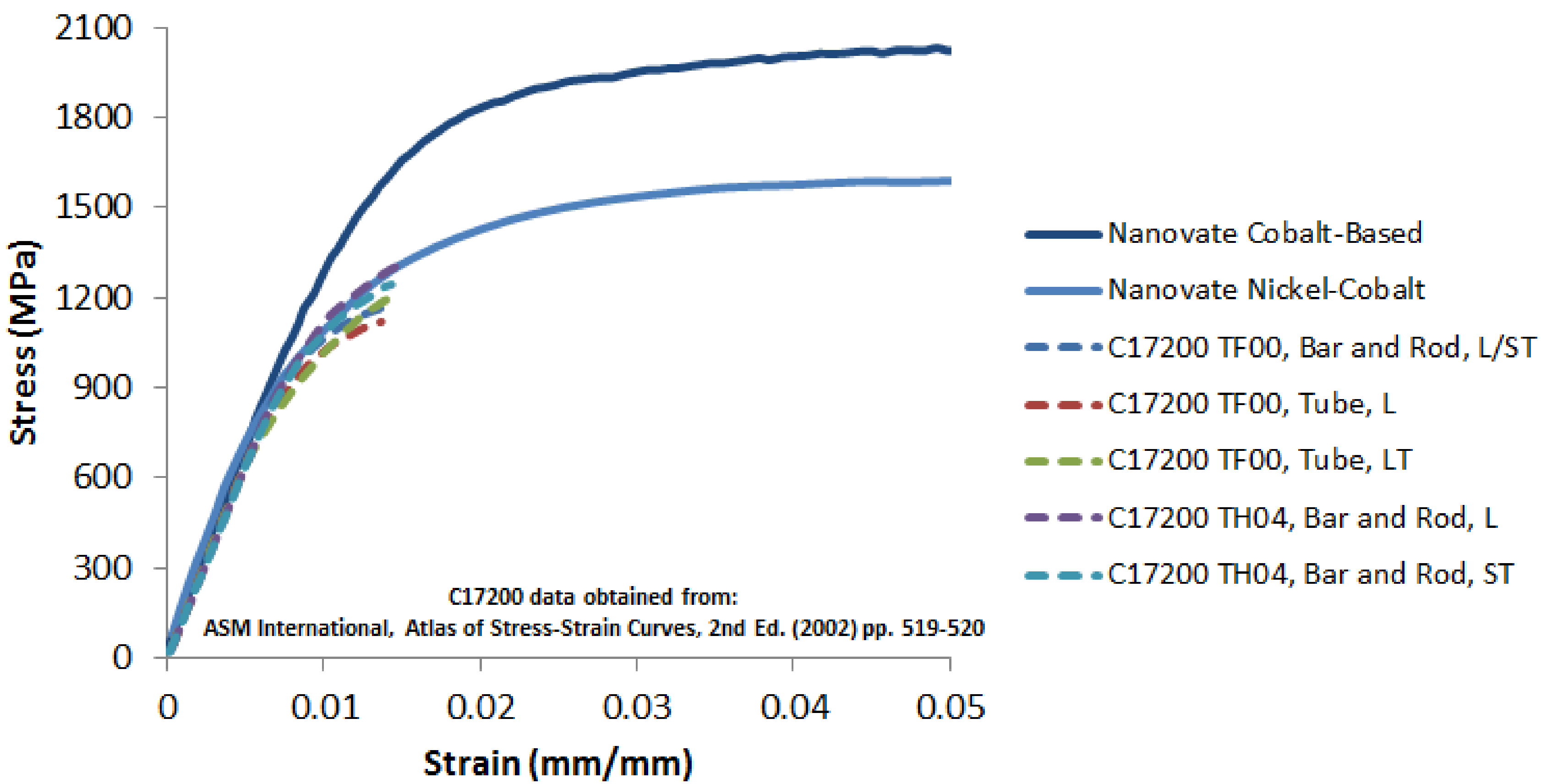



| Material | 0.2% Yield |
|---|---|
| CuBe TF00 | 973 ± 42 MPa |
| nNiCo | 1508 ± 14 MPa |
| nNiCo ML1 | 1640 ± 40 MPa |
| nNiCo ML2 | 1373 ± 23 MPa |
| nCo-based | 1967 ± 76 MPa |
| Cu (pyro) | << CuBe TF00 |
| nCuNi | 1493 ± 61 MPa |

**All Nanometals investigated (except pure Cu) had signicantly higher compression strength than CuBe**

# Mechanical Strength in Tension

- **Uniaxial Tension Testing (ASTM E8)**




**Tensile performance of Integran's Nanovate cobalt-based and nickel-cobalt metals is superior to copper beryllium (peak hardness);**

# Mechanical Property Summary

**Nanostructured cobalt-based alloy has much higher compressive and tensile strength than conventional bushing materials**

| Material | Compression Strength ksi (MPa) | Tensile Yield Strength ksi (MPa) | Tensile Ultimate Strength ksi (MPa) | Tensile Modulus of Elasticity (GPa) |
|---|---|---|---|---|
| **Nanostructured Cobalt Alloy** | 285 ksi (1967 MPa) | 225 ksi (1550 MPa) | 290 ksi (2000 MPa) | 18855 ksi (130 GPa) |
| **Copper Beryllium (C17200-TH04)** | 142 ksi (973 MPa) | 172 ksi (1185 MPa) | 190 ksi (1310 MPa) | 18855 ksi (130 GPa) |
| **Nickel Aluminum Bronze (C63000)** | 110 ksi (760 MPa) | 68 ksi (470 MPa) | 110 ksi (760 MPa) | 16700 ksi (115 GPa) |

# Summary of Frictional Properties

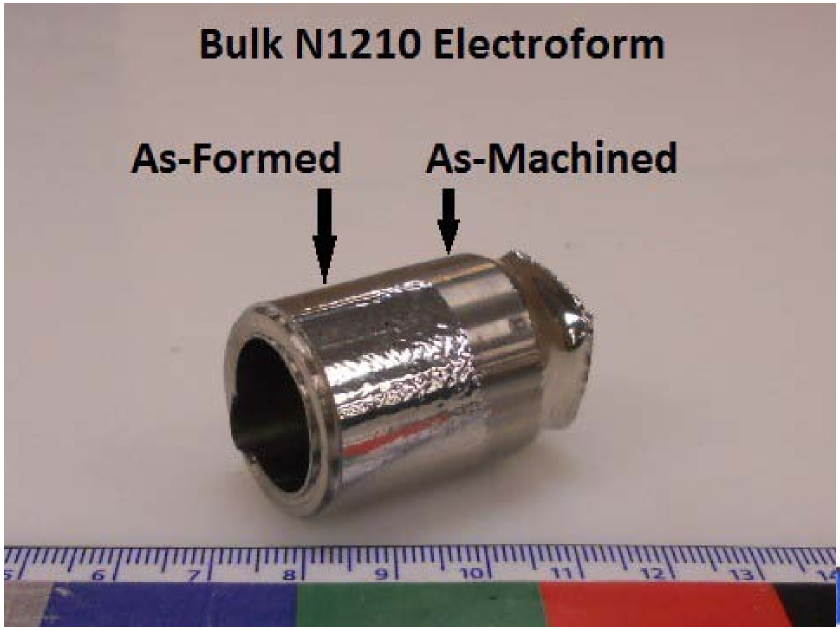
**Nanostructured cobalt-based bushings have low coefficient of friction against standard mating pin materials**

| Bushing /Mating Material | Hard Chrome coated HSS | HVOF (CoCr-WC) coated HSS | Nano Cobalt coated HSS |
|---|---|---|---|
| **Nanostructured Cobalt Alloy** | 0.42 | 0.46 | 0.36 |
| **Copper Beryllium (C17200-TH04)** | 0.73 | N/A | 0.65 |
| **Nickel Aluminum Bronze (C63000)** | 0.48 | 0.45 | 0.45 |

*COF obtained from Pin-on-disk testing per ASTM G99

# Subscale Bushing Testing

Fabricated solid nanostructured bushings via electroforming for sub-scale busing testing

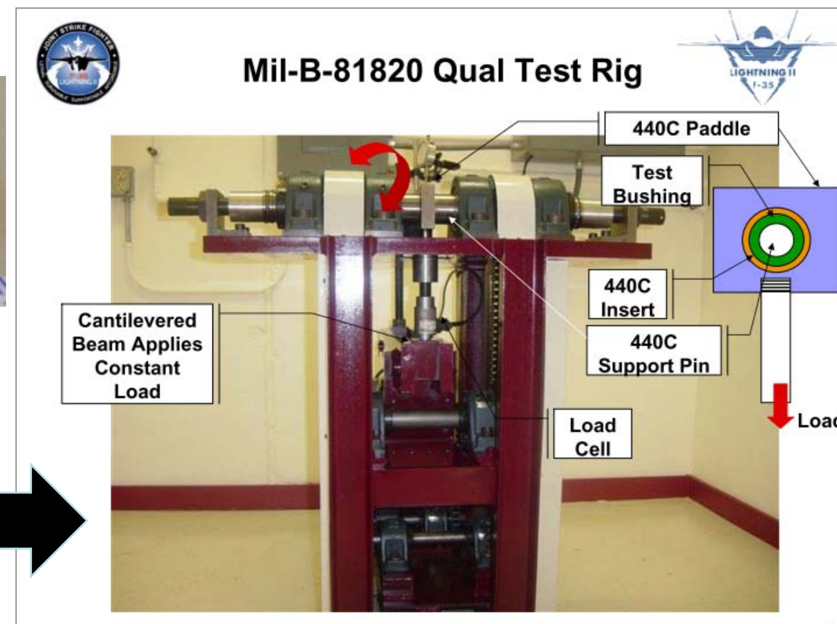



Geometry specific to
**LHM-010 bushing test**
(Tested at Cradin Aerospace)

# Subscale Bushing Testing

- <u>Task II-2:</u> **Bushing Performance Testing**
  - ♦ **Bushings fabricated to LHM-010/MIL-B-81820 and tested by Cradin Aerospace (Boerne, TX) using a hardened 440C steel pin**
  - ♦ **Test consists of loading the pin in 200 lbs load increments and rotating ±45° for 200 cycles before stepping up to the next load**
  - ♦ **Pass consists of loading to 10,000 lbs (~50 ksi bearing stress) and run-out of 2000 cycles**

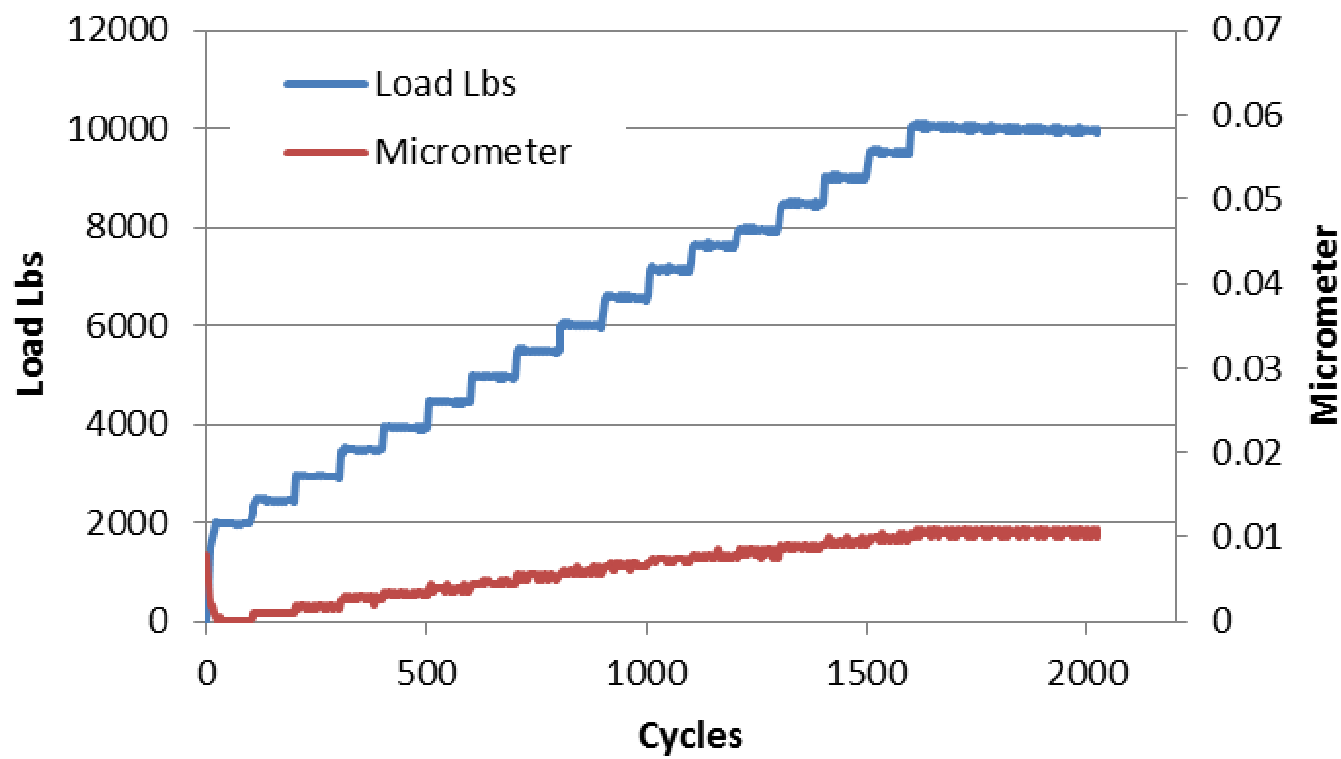

**Image from Scott Fetter, 2009 ASETS Presentation**
**Cradin Aerospace Equipment**



# Sub-scale Bushing Performance

Nano Co-alloy bushings performed exceptionally well

- **Excellent alloy strength; Low bushing noise; Low bushing temperature increase (10,000lbs = ~50ksi bearing stress)**

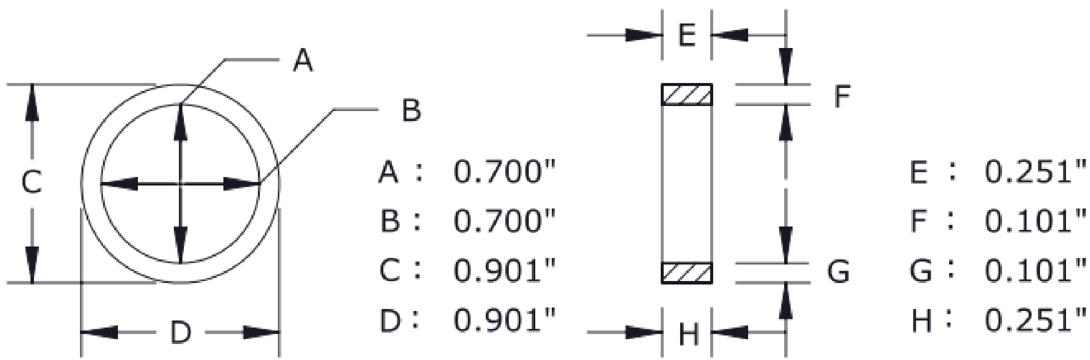


# Subscale Bushing Performance

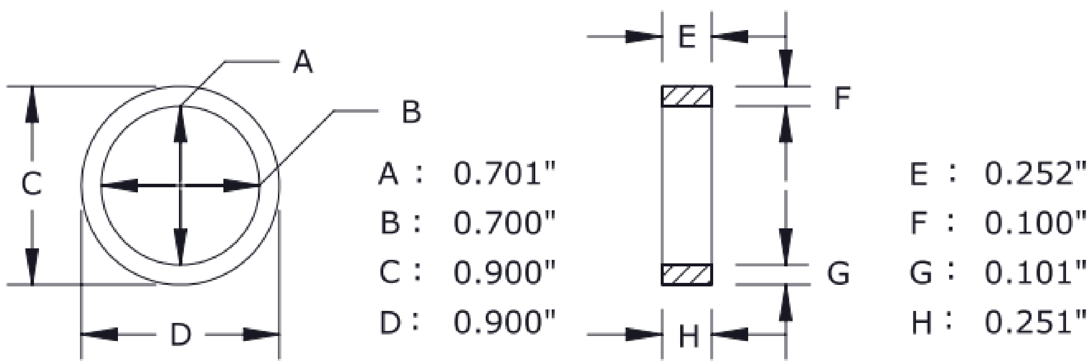
## Nanovate bushings have minimal deformation

- Less than 0.001” wear and no measureable wall flattening

Dimensions - Prior to Testing



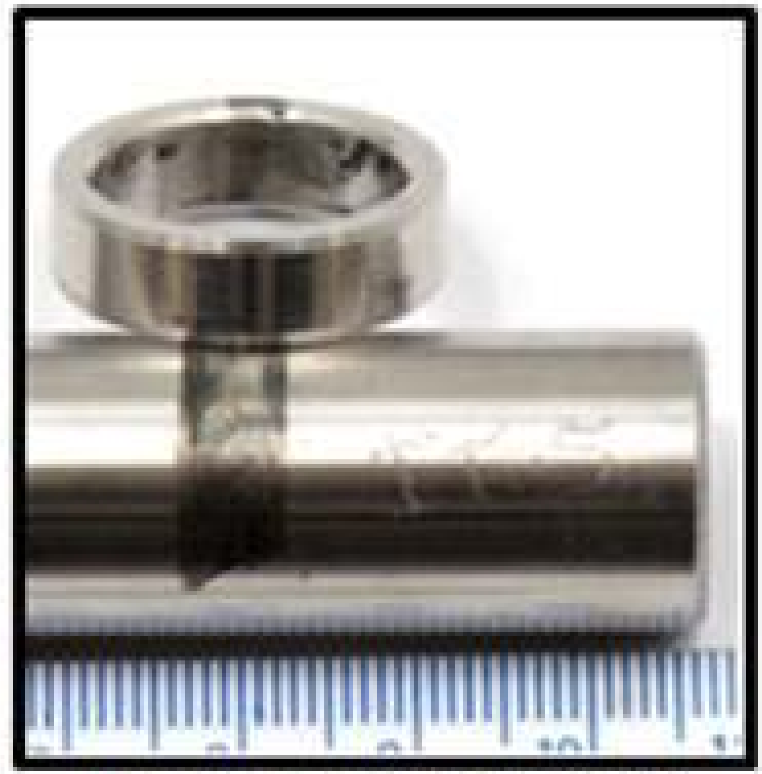

Dimensions - After Testing



# Sub-scale Bushing Performance

Nanovate bushings perform favourably to CuBe:

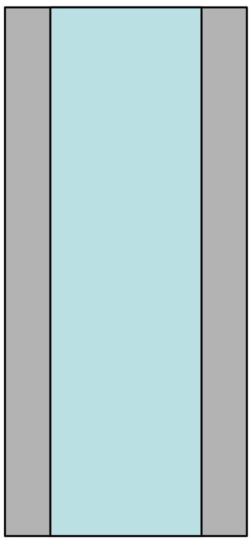
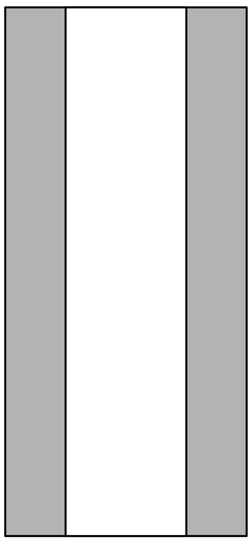
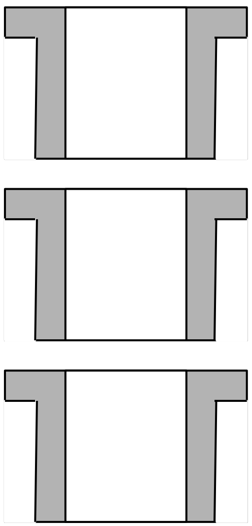
Cu-Be Bushing: MP 35N Pin
1725 cycles total
125 cycles at 10,000 lbs



Nano Co-alloy Bushing: 440C Pin
2000 cycles total
400 cycles at 10,000 lbs

# Electroformed Nanometal Bushings

- Near Net Shape Manufacturing Process with high ‘buy-to-fly’ ratio
- Cost effective due to less material waste during machining

| **Step 1 -** Electroform desired thickness (~0.25”) onto temporary mandrel | **Step 2 -** Remove mandrel | **Step 3 -** Machine Bushings |
|---|---|---|
|  |  |  |

# Prototype Nanometal Bushings

Nanovate bushings samples – Diameter range from 0.5” to 2.5” fabricated to date

# Cost Analysis

## ROM Cost Analysis

- Additive manufacturing approach **significantly reduces <u>material waste</u>** and **<u>cost</u>.**

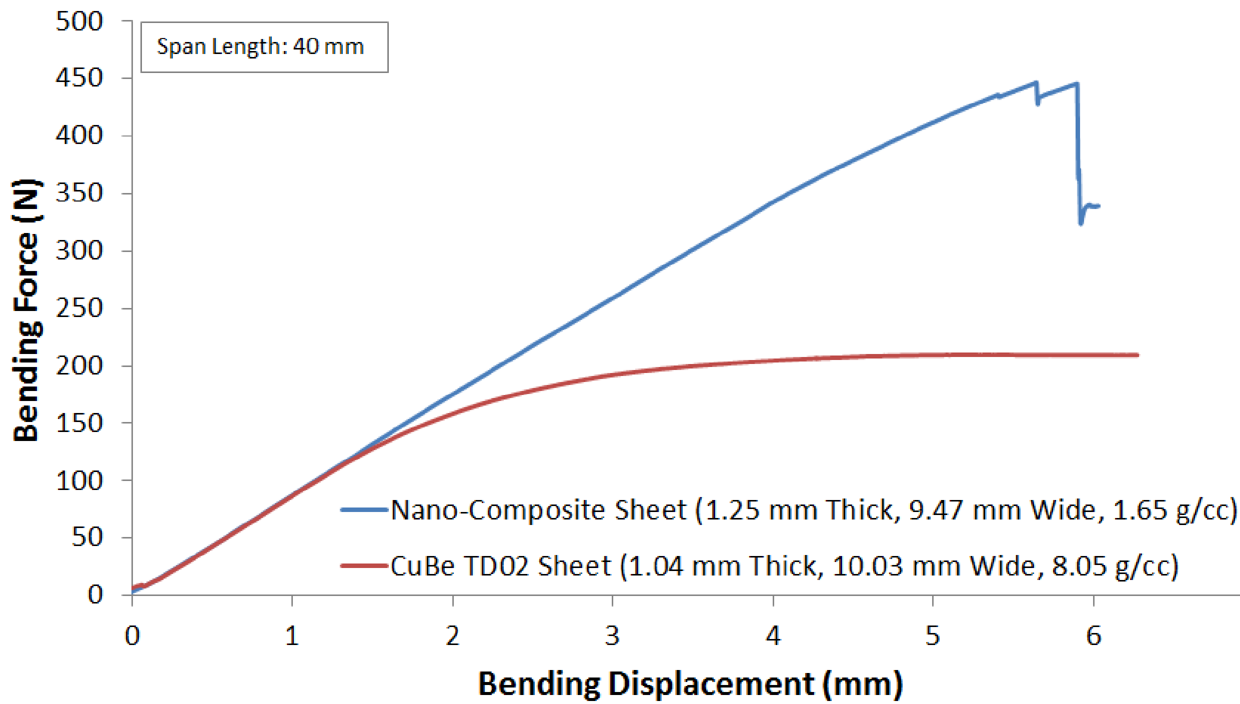
| Material | Bushing Diameter | Material Required (lbs) | Material Cost ($) | Material Waste (lbs) |
|---|---|---|---|---|
| CuBe | 2” | 10.3 | $124 | 86% |
| | 3” | 23.2 | $279 | 90% |
| | 4” | 41.3 | $496 | 93% |
| nCo-alloy (Additive Manufacturing) | 2” | 1.4 | $52 to $173 | - |
| | 3” | 2.3 | $81 to $271 | - |
| | 4” | 3.1 | $111 to $369 | - |

- **Assumptions – CuBe bushing machined from solid rod to 0.25” wall thickness, 12” rod length, Cost of CuBe: 12$/lb, Cost of electroformed nCo: 3-10x base metal cost (36-120$/lb)**

# Summary – Nanometal Hybrid Foil

## Proof-of-Concept for Sheet/Foil Applications

- **Nanometal-composite hybrids can be designed to possess similar bending stiffness and higher elastic limit at similar sheet thickness but <u>at <30% the weight of copper-beryllium</u> with improved fatigue resistance**



# Results Summary

- SERDP Project was successful in meeting original objectives
- Electroformed nano Co-alloy was tested and evaluated as an alternative to Cu-Be, demonstrating:
  - ♦ Significantly higher tensile and compressive yield strength than CuBe
  - ♦ Low coefficient of friction against various ‘pin” materials
  - ♦ Excellent galling resistance
  - ♦ Superior performance than CuBe in highly-loaded subscale bushing test
- Nanometal/Composite Hybrid show good promise for leaf spring/contact
- Looking for interested DoD and commercial partners to continue the project to the Dem/Val stage.